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Detecting Delamination in Concrete Bridge Decks

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The corrosion induced deterioration of concrete bridge decks is a serious problem in locations where deicing chemicals are used. The detection of subsurface fracture planes, or delaminations, is necessary when determining the need or priority for repair and when preparing documents for a repair contract.

The accuracy and appropriateness of manual methods of detecting delamination is compared with that of a commercial delamination detection device in widespread use. A single, heavy chain is a practical and efficient means of manually identifying delaminations.

Infrared thermography has been found capable of detecting delamination because there is a difference in the surface temperature of sound and delaminated concrete under certain atmospheric conditions. The article describes the equipment and the factors affecting the infrared imagery when used at ground level and from the air. The technique has the potential to become a routine operational procedure.

Keywords: bridge decks: concretes; corrosion; deicers; **deterioration; temperature measuring instruments.**

Introduction

The corrosion induced deterioration of concrete bridge decks is a serious problem in all areas where deicing salts are used for snow and ice control. As the reinforcing steel corrodes, it expands and creates a crack or subsurface fracture plane in the concrete at or just above the top reinforcement. The fracture plane, or delamination, may be confined to a local area or may extend over a substantial portion of the deck if the concrete cover is uniformly low. It is not uncommon for more than one delamination to occur on different horizontal planes above the reinforcing steel. If repairs are not made, the traffic loading and ice formation in the delamination during the winter months cause the concrete to spall, thereby reducing the riding quality of the deck and, eventually, its structural integrity.

Highway agencies need to detect delaminations, which are not visible from the deck surface, under the following circumstances:

1. When conducting a bridge deck condition survey to determine if repairs are needed
2. when setting priorities for repair
3. when the need for repairs is already established and the most appropriate method of repair must be identified and contract documents prepared.

In the first two cases the delaminations need only be determined approximately since it is the presence and extent of the delaminations, rather than their precise location, which determines the future course of action. When it is known that repairs will be undertaken an accurate measurement of the size and location of the delaminated concrete is required, especially if it is to be removed as a bid item in the repair contract.

Methods of detecting delamination

A delamination in the concrete causes a dull sound to be heard when the deck surface is struck. Methods of detecting delamination currently in routine use utilize this characteristic.

The detection of delaminations by infrared thermography is based on the difference in surface temperature which exists between sound and unsound concrete under certain atmospheric conditions. The idea is not new; an exploratory study undertaken in 1969 succeeded in detecting delaminations in concrete specimens in an outdoor location.[1] More recently the technique has been used to identify delamination in concrete bridge decks.[2,3]

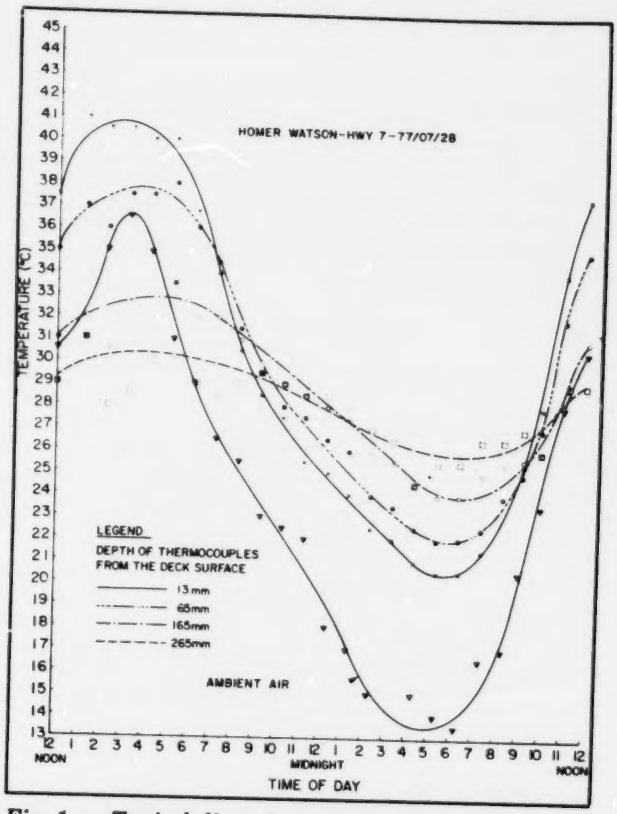

Fig. 1 — Typical diurnal temperature distribution in a thick slab deck in summer.

Fig. 1 illustrates a typical temperature variation over a 24 hr period in the top 260 mm (10 in.) of a thick slab deck with an exposed concrete surface in Ontario on a summer day under clear skies. A substantial temperature gradient was recorded in the top 65 mm (2½ in.) of the deck and this coincides with that part of the deck where delaminations occur. During the hottest part of the day the concrete temperature decreases with the depth below the deck surface and at night the situation is reversed. Similar temperature distributions have been recorded on thin slab decks in both summer and winter, though the temperature gradient is less in win-

ter. Fig. 2 shows the temperature variation in sound and delaminated concrete, in a period of moderate heating, measured by thermocouples installed 6 mm (0.2 in.) below the surface of a thin slab deck. During the test period the difference in temperature between the solid and the delaminated concrete reached 3 C (5 F).

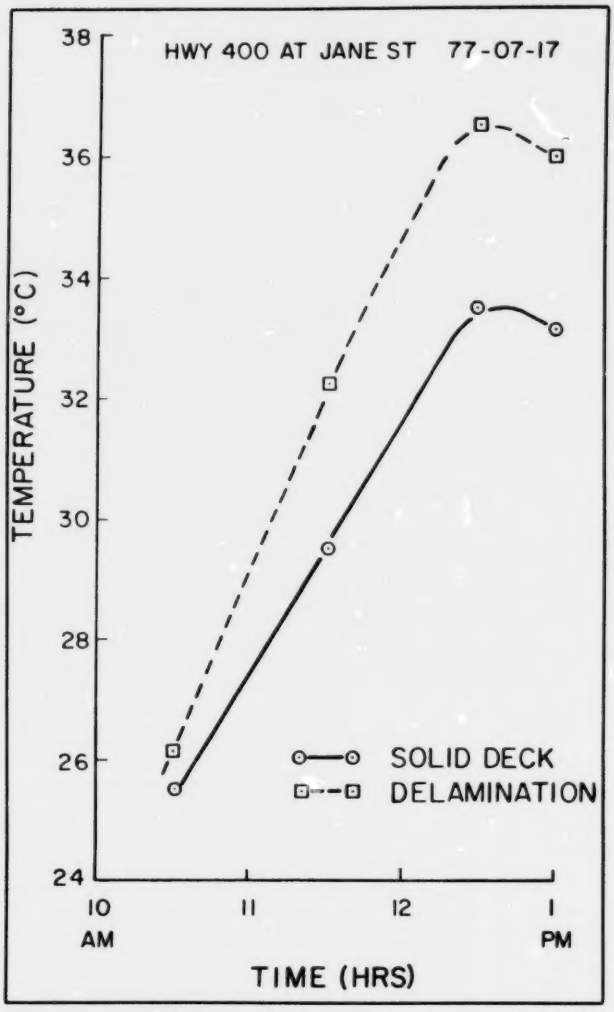

Fig. 2 — Difference in temperature between solid and delaminated concrete.

Manual methods

A number of hand tools, including hammers, steel rods, and chains, have been used to strike the deck surface, working progressively over the entire deck. The interpretation of the sound produced is subjectively assessed by the operator.

The use of a hammer is tedious because the operator works in a crouched position and covers only a small area of the deck at a time. The steel bar enables the operator to work in an upright position but its use is also very time consuming. Neither a hammer nor a steel bar is a satisfactory striking object because the sound produced depends on the vibrational characteristics of the hammer or rod.[4] If the striking object is highly resonant, the difference between sound and delaminated concrete may be difficult to distinguish. A steel mass tied at the end of the piece of rope does resonate when struck and has been used successfully.[4] This apparatus may also be dragged across the deck surface in the same way as a chain.

The chain drag may take several forms from a single, heavy logging chain approximately 2 m (6.6 ft) long to an apparatus constructed from four or five segments of chain about 0.5 m (1.6 ft) long attached to a 0.5 m long piece of tubing by means of a flexible coupling. A handle is attached to the midpoint of the tube. The device is swung from side to side allowing the chains to drag across the deck surface. When a single chain is used, it is passed over the deck surface with a whiplike action, permitting a large area to be covered rapidly. When a delamination is located, the length of chain in contact with the deck is shortened and the limits of the delamination are delineated and marked directly on the deck using crayon or paint. Experience has shown that a single heavy chain having a 50 mm (2 in.) link and weighing 2.2 kg/m (1.5 lb/ft) meet the requirements of speed and accuracy, especially when work must be carried out where the noise of traffic in adjacent lanes makes identification of the sound difficult.

The normal procedure for recording delamination is to mark a grid on the deck and measure the location and area of the delaminations relative to the grid lines. The procedure is very time consuming especially when numerous, small areas of delamination are present. Often field staff will square off delaminated areas to simplify the recording though this may introduce serious errors in calculating quantities for contract documents. Designers have also been known to increase the quantity of delaminated concrete to be removed to cover any omissions in the field measurements and to add a further factor to account for delaminations which may develop between the time of measurement and execution of the repair contract. Unless this series of upward revisions is carefully controlled, the estimated quantity of concrete removal may be considerably in error.

Mechanical and acoustical devices

One of the first mechanical tapping devices for delamination detection was developed by the Kansas Department of Transportation.[5] The apparatus was wheeled along the deck and small wooden blocks tapped the deck surface at regular intervals. The sound emitted still had to be interpreted by the operator and the location of the delaminations recorded manually.

The Texas Highway Department, in cooperation with the Texas Transportation Institute, developed a portable electronic instrument for detecting and recording delaminations which does not require the subjective judgement of the operator.[4,6] The machine, which is now commercially available, consists of three basic components, a tapping device, a sonic receiver, and a system of signal interpretation. Its design and construction are described in detail elsewhere.[4] The instrument is wheeled along the deck and the instrument receives and electronically interprets the acoustical signals generated by the instrument and reflected through the concrete. The distance between adjacent passes is usually about 1 m (3 ft) though wider spacings are sometimes used. The output is presented as a wave form on a two-pen chart recorder. Programs have been developed which will generate a site plan and record the areas of delamination on the plan directly from the instrument output.

An example of the results of a survey completed on a portion of a structure is shown in Fig. 3 which also illustrates the delaminated areas as detected by a chain drag for comparative purposes. The number of passes of the instrument was doubled to increase the accuracy of the survey and a considerable effort was expended to produce an accurate manual survey. During the test it was observed that the instrument recognized some spalls as delaminations and consequently the area of 15.4 m² (18 sq yd) shown in Fig. 3 as delaminated includes some, but not all, of the spalls indentified in the manual survey. Even when this factor is ignored the instrument identified only 67 percent of the delaminated areas detected by the chain drag. It is normal commercial practice to classify the severity of the delaminations recorded by the detector as mild, substantial, and severe though the physical significance of these arbitrary classes is not clear. These classes have been omitted in Fig. 3 for clarity.

The instrument has been reported to be capable of detecting delaminations up to 115 mm (4.5 in.) below the surface of decks with an asphalt wearing course and up to 65 mm (2.6 in) below the surface of exposed concrete deck slabs.[4] However, a survey on a large asphalt paved deck in Ontario indicated the deck was extensively delaminated. Subsequent removal of the 75 mm (3 in.) thick wearing course showed the deck to be free from delaminations and the signals indicating the presence of a physical discontinuity were attributed to poor bond between the bituminous concrete and the deck slab. Delaminations are usually associated with active corrosion of the reinforcing steel and it may be necessary to conduct a delamination survey in conjunction with a half-cell survey to obtain corroborating evidence of the presence of delaminations in asphalt covered decks.

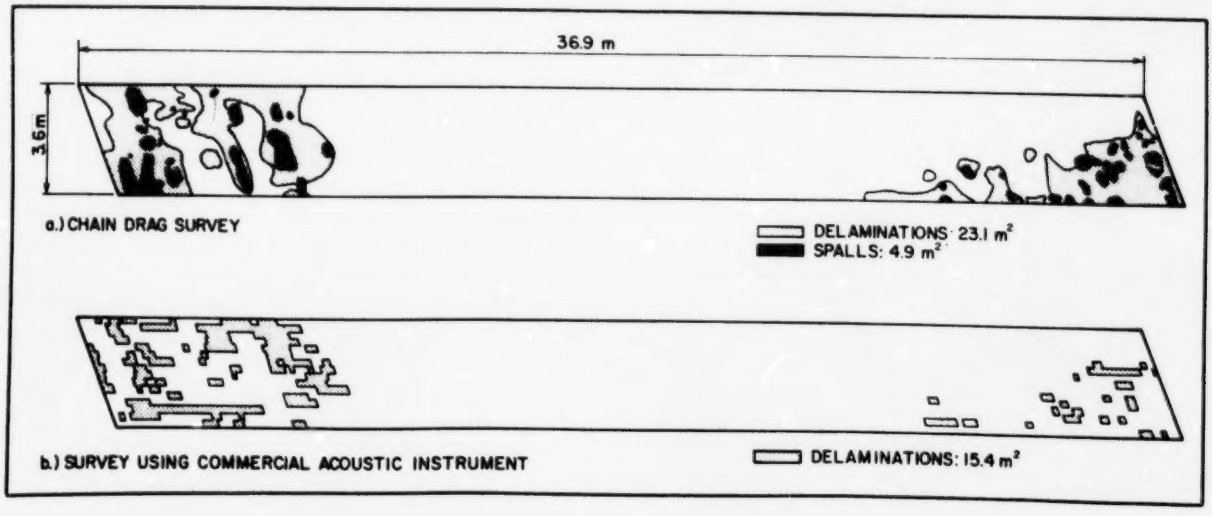

Fig. 3 — Comparison of delaminated areas identified by a chain drag and an acoustical device.

Infrared thermography

Equipment

An infrared detection system using an indium antimonide photovoltaic detector with a spectral range of 2 to 5.6 μm (0.00008 to 0.00022 in.) was used in an investigation undertaken to determine the feasibility of detecting delaminations by infrared thermography.[3] The equipment, which is shown in use on a bridge deck in Fig. 4, consists of a camera, display monitor, and power source. Similar equipment fitted with a videotape capability and a vibration-free mount was used in some of the airborne testing. The effective temperature range of the instrument is from -20 C to 900 C (-4 to 1652 F) with a sensitivity of better than 0.2 C (0.36 F). Infrared film cannot be used in place of the infrared scanner because the film has a temperature range of 250 to 500 C (482 to 932 F) and cannot detect differences in bridge deck temperatures which differ by only a few degrees from the ambient air temperature.

The image from the camera is displayed on a cathode ray tube and indicates the temperature of the surface of an object in a continuous range of gray tones from black to white. The cooler areas can be displayed as darker in the normal mode or brighter in the inverted mode. The display also has an isotherm function which superimposes a bright contour on areas of equal temperature. A color monitor is also available for presentation of the image in a 10 color range. Either a 35 mm or an instant camera can be mounted on the monitor for a hard copy record of the display image. A 20 deg lens was used in ground level testing and a 7 deg lens for the airborne testing. A solar filter was used during daytime testing to remove the reflected short wavelength radiation from the sun and to decrease the effect of shadows.

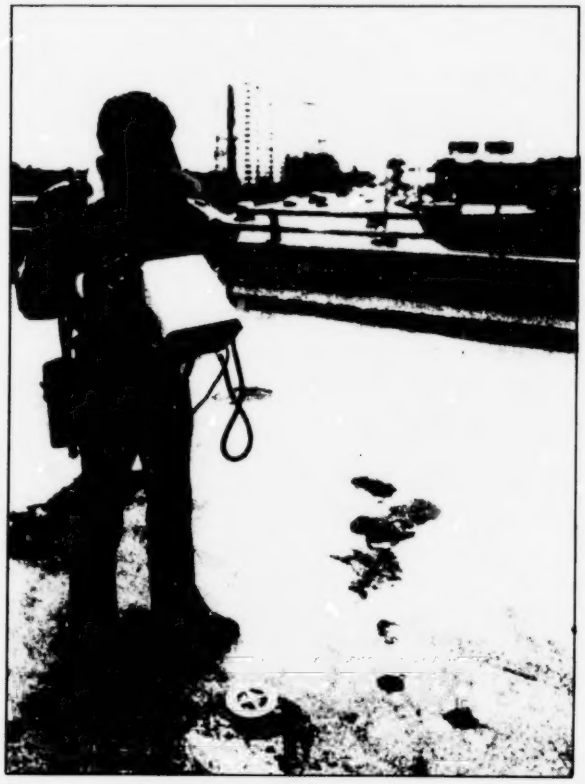

Fig. 4 — Infrared thermovision equipment with instant camera attached.

The quality of the thermal images was not as crisp as expected. This was partly due to changes in the emissivity of the concrete surface and partly due to small differences in the surface temperature across the deck. The hard copy reproductions lacked some of the definition visible in the image displayed on the monitor which was brighter and had more contrast. The application of the color images has been discussed elsewhere[3] and, although useful in special circumstances, interpretation of the physical phenomena associated with each color level is difficult.

Factors affecting the thermal image

Infrared thermography is normally used for the measurement of the surface temperature of bodies with an internal source of heat; for example, in heat loss studies of buildings or electrical components. In the case of bridge decks it is reflected heat which is being measured and this is more difficult because reflected heat is much more sensitive to environmental factors.

Because the scanner measures differences in the surface temperature of the bridge, the distinction between sound and unsound concrete was expected to be most visible during periods of rapid heating and cooling. During daytime tests, it was found that the sun shining on the deck was effective in raising the deck temperature almost immediately and creating temperature differentials which enabled the areas of sound and delaminated concrete to be distinguished. The longer period of solar radiation, the greater the temperature differentials became and the more clearly the delaminations were defined. In the course of tests undertaken in both summer and winter, temperature differentials stabilized at 1.5 to 4.5 C (2.7 to 8.1 F) during midafternoon, depending upon the weather conditions. In four night-time tests the temperature differentials stabilized at approximately 2 C (3.6 F) around 2:00 a.m. Temperature differentials were found to exist at almost any time of the day or night except around sunrise and sunset. Shortly after sunset, when the deck begins to cool, the surface temperature of the delaminated areas changes from being hotter to cooler than the average deck surface temperature and the temperature differential disappears for a short time. The reverse situation occurs shortly after sunrise.

Although the scanner could detect a temperature differential of 0.2 C (0.36 F), a higher differential is

desirable to counteract the effect of such factors as differences in emissivity caused by polishing of the concrete in the wheel paths or debris on the deck. A differential of 1.5 C (2.7 F) was considered to be a reasonable, practical minimum for adequate resolution in the thermograms with a 2 C (3.6 F) differential being desirable. As was expected, an increase in cloud cover reduced temperature differentials. Ambient temperatures within the range -5 to 28 C (23 to 82 F) investigated were not found to have a significant effect on the visibility of the delaminations in the thermograms since it is the temperature differential which is important and not the ambient air temperature. Differentials do, however, tend to be greater in summer than winter because of the greater intensity of the solar radiation in summer. Wind was found to increase atmospheric attenuation of the reflected heat rising from the deck and its effect was not predictable. Consequently, testing when the wind speed exceeds 25 km/h (15.5 mph) should be avoided.

Moisture on the deck surface prevented identification of delaminated areas because of its different emissivity and its tendency to mask surface temperature differences.

During one series of night tests, surface temperatures of 0.3 to 2 C (0.5 to 3.6 F) less than the average deck temperature were recorded. Five locations were selected to represent the range of temperature differentials and subsequently cored. Where delaminations were found, the average thickness of the delaminated concrete was recorded. The data is presented in Table 1 and shows a correlation between temperature differential and thickness of the delaminated concrete. Core "A," which was in a solid part of the deck, appeared slightly cooler than the average deck temperature, possibly because of its location in the middle of several delaminated areas. Thermocouples were later installed 6 mm (0.23 in.) below the deck surface on the concrete adjacent to the location of the cores reported in Table 1. During daytime measurements it was found that the shallower delaminations heated faster and to a higher temperature than the deeper delaminations, thereby confirming the relationship between surface temperature and depth of delamination which was observed when using the scanner.

TABLE 1 — Relationship between surface temperature differential and thickness of delaminated concrete

Core	Temperature cooler than deck average, deg C	Average thickness of delaminated concrete, mm
A	0.3	solid deck
B	0.6	24
C	1.0	21
D	1.8	18
E	2.0	10

Scaling and airborne testing

The first series of tests were carried out by an operator standing on the deck and holding the camera. Although the feasibility of using thermography to identify delaminations was demonstrated, this procedure was impractical because of the limited field of view and the difficulty of constructing composites from oblique photographs.

A bucket truck was used to scan a bridge deck at heights ranging from 1.5 m to 20 m (5 to 65.6 ft). When the surface temperature differentials were greater than 2 C (3.6 F), the accuracy and definition of the delaminations were adequate at all heights. Aluminum targets, as shown in Fig. 4, were placed on the deck at 1.2 m (4 ft) centers to scale the images and aid in construction of the composites. A typical composite thermogram, which was taken at night from a height of 8 m (26 ft) is shown in Fig. 5. The targets were readily identifiable but the scales in the composite were not consistent because of the oblique angle of view.

Such thermograms are difficult to piece together. The problem can be minimized by increasing the height at which the thermograms are taken, thereby decreasing the number of photographs in the composite.

Two alternatives were available to produce a scaled image: to use a surface coated mirror to obtain true vertical images; or to use the scanner from an airborne platform to enable one or two images to cover the entire bridge deck.

Limited testing was done with a mirror because of the lack of availability of a suitable product. Furthermore, the airborne application offered the additional benefit of not requiring lane closures, which can be very expensive, particularly on urban freeways.

The airborne testing was carried out by mounting the equipment in a helicopter with a door removed. Several bridges known to be delaminated were photographed. Unfortunately the structure used in the delamination survey and the ground level testing was not a suitable candidate for experimental flights because of its location in close proximity to residential high-rise buildings.

The first flights were undertaken at heights ranging from 15 m to 400 m (49 to 1312 ft) and in weather conditions ranging from clear and sunny with 15 C (59 F) temperatures to overcast with a temperature of 18 C (64 F). The thermal images were generally poor and in some cases the delaminations were not visible. Where the difference in the air temperature between the deck surface and the hovering height exceeded 2 C (3.6 F), temperature differentials on the deck surface were not easily recognized by the scanner. Wind was also found to have a more significant effect than at ground level and not only disturbed the thermals rising from the deck but made the helicopter difficult to hold sufficiently steady for good quality photography.

Fig. 5 – Panoramic thermogram composite from 8 m (26 ft).

Fig. 6 – Thermogram composite from 15 m (49 ft). The white areas at each end represent bituminous concrete.

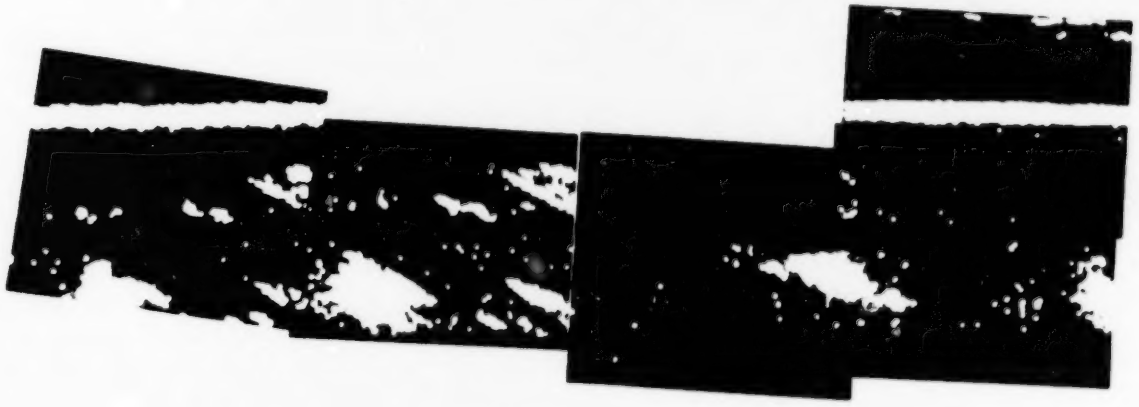

Fig. 7 – Thermogram composite from 15 m (49 ft) using isotherms to delineate delaminations.

The thermograms reproduced in Fig. 6 were taken on a sunny day with a ground level temperature of 22 C (72 F), a temperature of 20 C (68 F) at a height of 75 m (246 ft) and a wind speed of 0 to 5 km/h (0 to 3 mph). Under these conditions the delaminations were clearly visible. The white line on the top edge of the thermogram is sand remaining from winter maintenance operations. Fig. 7, also taken at a height of 15 m (49 ft) shows the isotherm technique used for outlining the delaminated areas. The area shown corresponds to the center of the bridge deck in Fig. 6. The use of the isotherm function increases the contrast of the image and may prove to be a useful method of representing delaminations because of the better definition in the hard copy. The bridge deck illustrated in Fig. 6 and 7 was also carefully tested using manual methods. The areas shown to be delaminated in the thermal images were found to be approximately 80 percent of the area found to be delaminated using a chain drag.

Discussion

The manual methods of detecting delamination in concrete bridge decks have the disadvantages of requiring lane closures to perform the investigation, necessitating the marking of a grid directly on the deck, subjectively interpreting the presence of delamination, and painstakingly recording the location of each delamination with respect to the grid lines. Of the manual methods which have been used in Ontario, a single heavy chain has been found to be most suited to the requirements for speed and accuracy of measurement. Despite the drawbacks of the chain drag, it is still the most practical method, considering both accuracy and economy, of identifying delaminated areas; a factor which has previously been recognized.[7] It has also been reported that the chain drag is more reliable than the hammer in some situations.[8] In cases where repairs will be carried out soon after the survey is made, permanently outlining the delaminations on the deck surface obviates duplication of this task.

The commercial delamination detection instrument eliminates the task of marking a full grid on the deck required by the manual methods since only the survey lines need be located. The instrument also has the advantages that it eliminates most of the subjective interpretation by the operator and is not affected by noise from adjacent traffic. The workload is also independent of the number and shape of the delaminations, a factor of some significance with manual methods since small, irregular shaped delaminations require considerable time to locate and record on a site plan. There is, however, a substantial loss in accuracy when using this equipment. Even with a close spacing between runs, 0.5 m (1.6 ft) in the case of the investigation reported here, a significant proportion of the delaminated areas were not identified. The errors could cause serious problems in contract administration if data from such a survey were used to prepare contract documents. Van Daveer also noted that the instrument is not well suited to isolating specific areas requiring repair.[7] The instrument is more useful in condition surveys directed at determining a need for repair or establishing priorities for repair, in which cases the accuracy of the results is tolerable.

The accuracy achieved in the infrared thermography study was better than with the acoustical device but, when employed from the air, still not sufficient for use in preparing contract documents. The chief advantage of this method is that the delaminations are detected by remote sensing, eliminating the need for traffic closures and, thereby increasing safety and reducing delays to the road user. The procedure cannot be considered operational yet, but it appears that airborne thermography in which several structures are examined in a single flight will become both feasible and economical. Scaling the images is one difficulty to be overcome although the use of a videotape which can be analyzed in the office and stereo images prepared for plotting holds considerable promise. A serious problem in urban areas is that air regulations severely limit low level flights and more work is needed to determine if acceptable images can be obtained from higher altitudes.

Conclusions

1. Manual methods, though tedious, are the most practical means of detecting delamination in concrete bridge decks from the standpoint of accuracy and economy. A single, heavy chain is the preferred equipment.
2. The results produced by the commercial delamination detector were less accurate than those using a chain drag and were better suited to preliminary condition surveys where lesser accuracy is tolerable.
3. Infrared thermography can be used, from both the ground and the air, to detect delaminations because of the difference in the surface temperature of sound and delaminated concrete which exists under certain atmospheric conditions.
4. Temperature differentials may occur at any ambient temperature but are greatest during periods of rapid heating and cooling.
5. Differences in the surface temperature of the concrete are indicative of the thickness of the delaminated concrete.
6. Although further work is needed before infrared thermography is used routinely by highway agencies, the technique has the potential to become an operational procedure.

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